ASTROMETRY VLBI IN SPACE (AVS)

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1. MISSION GOALS

This paper describes a proposal for a new space radio astronomy mission for astrometry, using Very Long Baseline Interferometry (VLBI), called Astrometry VLBI in Space (AVS). The ultimate goals of AVS are improving the accuracy of radio astrometry measurements to the microarcsecond level in one epoch of measurements and improving the accuracy of the transformation between the inertial radio and optical coordinate reference frames. This study will also assess the impact of this mission on astrophysics, astrometry, and geophysics.

The primary scientific goals for the AVS mission are:
1) A two order of magnitude irnprovernent in solar system tests of General [relativity,
2) A rigorous determination of extragalactic source stability and estimation of proper motions of extragalactic radio sources of possible cosmological origin,
3) Construction of the first global astrometric surveys in several frequencies, and a one order of magnitude or better improvement in the tie between the radio and optical astrometric reference frames.

The secondary mission goals include:
1) Tracking of interplanetary spacecraft on a target of opportunity basis,
2) Several order of magnitude improvements in terrestrial time transfer,
3) Test of Frame Dragging at the 20% level using the Sagnac effect,
4) Monitoring of changes in extragalactic radio sources at very high angular resolution,
5) Improvements in geophysical determinations of geocenter motions and changes in Earth's rotation.

The proposed mission will be capable of a wide range of measurements which are not prime goals or capabilities of the Space Very Long Baseline Interferornetry (SVLBI) missions currently under development. The proposed VLBI astrometric measurements can be implemented with much smaller orbital radio telescopes than those of the currently proposed SVLBI imaging missions with a corresponding savings in cost.

II. MISSION CONCEPT

Current ground-based VLBI radio astrometry angular accuracy is primarily limited by atmospheric propagation effects, and by the length of the longest attainable Earth baselines (-10000 km). Efforts to tie the radio and optical frames with observations of radio stars will be limited to the few-milliarcsecond level by the unmodeled angular difference between the optical and radio centers of emission.

The above astrometric limitations can be circumvented if the radio interferometer is placed in space. It is possible to establish a unified Celestial Refrence Frame and to tie an inertial Radio Refrence Frame, an Optical Reference Frame, and a Geocentric-Equatorial Reference Frame with unprecedented accuracy.

2.1. System Configuration

A basic element of the proposed mission is a space-based radio interferometer composed of two free-flying antennas. The antennas will be located in orbit such that they are visible to each other most of the time. A microwave (or laser) link will be established between the Space Radio Telescopes (SRTs) to provide a direct measurement of the radio interferometer baseline length, and synchronization of the L.O's and SRT's clocks. Along with radio interferometry equipment, each spacecraft will carry an optical beacon and optical (CCD) astrometry camera. The camera will determine the position of the optical beacon (the spacecraft with the radio telescope) relative to the optical reference stars (Figure 1) :

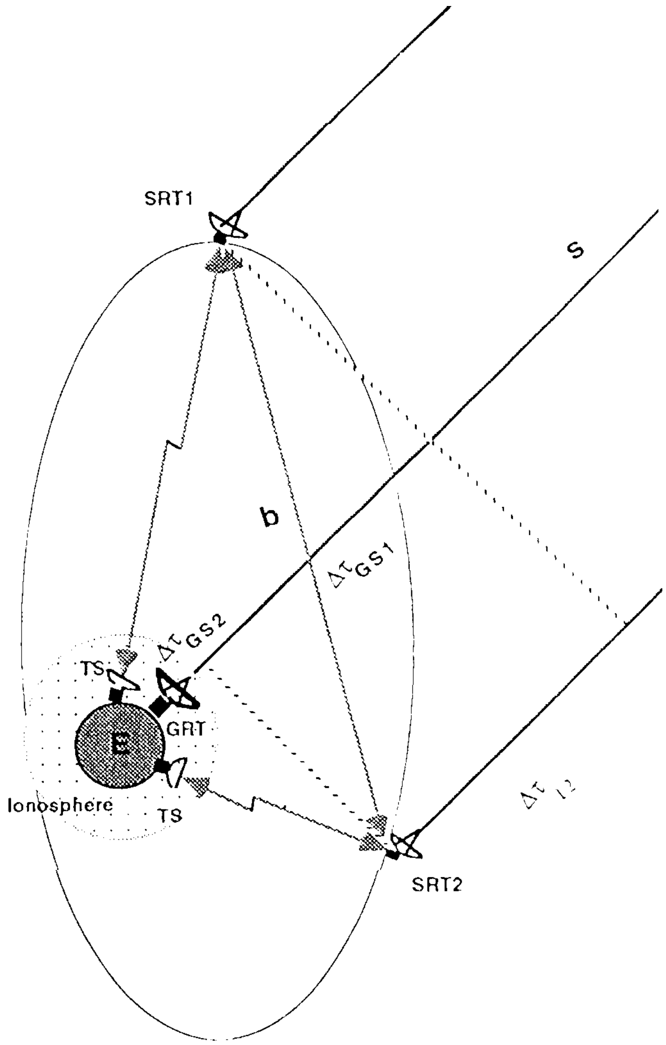

Figure 1. "Astrometry VLBI in Space" **Mission** Configuration

The advantages of such a configuration are [1 ,2]:

i) Direct determination of the baseline length and synchronization of SRT's local oscillators and clocks by a microwave link established between two spacecraft can, in principle, allow use of fringe phase for angular measurements, as in connected-element interferometry, instead of the group delay as used in Earth-based VLBI;

ii) Optical astrometry devices will provide the orientation for the radio interferometer baseline relative to the optical reference frame, thus the coordinates of the radio sources will be determined directly in the optical reference frame;

iii) Uncertainties in the Earth's rotation parameters, Earth's tides, etc. will not contaminate the orbiting radio interferorneter data unlike with Earth-based VLBI;

iv) Locating the interferometer outside the troposphere and ionosphere will exclude propagation effects in these media;

v) The baseline of the space-based radio interferometer (and, accordingly, its angular resolution) will not be limited by the Earth's diameter.

2.2. Size of Space Radio Telescope Antenna

The main cost-driving element of the SVLBI missions which are now under consideration and development is the cost of the antenna (see, for example IVS project study [3]). In order to use in space relatively small diameter antennas and thereby keep the cost of the mission relatively low, the astrometry observations of the space-based interferometer should be perlormed in conjunction with a single large-diameter ground-based radio telescopes [4].

Simultaneous astrometric VLBI observations by the system composed of two space-based radio telescopes and a ground-based radio telescope (GRT) can provide a relative time group delay (main value used in VLBI astrometry measurement) between two space radio telescopes $\Delta\tau_{12}$, and, accordingly, the coordinates of the radio sources as determined from the equation $c\Delta\tau_{12}=(\vec{b}\vec{s})$, which will not include an atmospheric impact (τ_{ATM}) and instrumental time delays in GRT equipment (τ_{id}) (see Figure 1).

To show this, the time delay measured between SRT2 and GRT ($\Delta\tau_{GS2}$) should be subtracte from the time delay between SRT1 and GRT ($\Delta\tau_{GS1}$):

$$\Delta\tau_{GS1} = \tau_{SRT1} - \tau_{GRT} - \tau_{ATM} - \tau_{id}$$

$$\Delta\tau_{GS2} = \tau_{SRT2} - \tau_{GRT} - \tau_{ATM} - \tau_{id} \qquad (1)$$

$$\Delta\tau_{GS1} - \Delta\tau_{GS2} = \tau_{SRT1} - \tau_{SRT2} = \Delta\tau_{12}$$

Here, $\vec{b}$ is the baseline vector of a space-based interferometer , $\vec{s}$ is the unit vector in the radio source direction, $\tau_{SRT1,2}$ is the propagation time from the source to the space radio telescope, and τ_{GRT} is the propagation time from the source to the ground radio telescope.

At the same time, simultaneous observations of a space radio interferometer combined with relatively small antennas with large ground-based radio telescopes will increase the signal-to-noise ratio (SNR) and, accordingly, decrease the stochastic error of radio astrometry measurements with a space-based radio interferometer.

It can be shown [4], that for a system with one ground radio telescope (diameter D_{GRT}) and two space radio telescopes (diameter $D_{SRT1}=D_{SRT2}$), the accuracy of the time delay measurements will be determined as:

$$\sigma\left(\Delta\tau_{12}\right)=\sqrt{\sigma\tau_{GS1}^{2}+\sigma\tau_{GS2}^{2}} \propto \sqrt{2}\,/\left(D_{GRT}\cdot D_{SRT}\right) \qquad (2)$$

Accordingly, if these measurements involve N ground radio telescopes with a diameter D_{GRT}, one can determine for each three-element subsystem (two SRT and one GRT) the value $\Delta\tau_{12}$. The resulting rms of time delay measurements can be averaged at N measure ments:

$$\overline{\sigma(\Delta\tau_{12})}^{N} \propto \sqrt{2}\,/\left(\sqrt{N}\cdot D_{GRT}\cdot D_{SRT}\right) \qquad (3)$$

Example: The use of two space radio telescopes with diameters of **4m** and ground-based radio telescopes with diameters of 70m is equivalent to making observations with two space-based radio telescopes with diameters of 23.5m; (70x4)=(16.7x16.7)=(23.5x23.5)/2 (where D_{SRT}=23.5 m, D_{GRT}=70m, N_{GRT}=4).

2.3. Performance of Orbiting Radio Astrometry Interferometer

The accuracy of the time delay $\sigma(\Delta\tau)$ and angular measurements $\sigma(\Delta\Theta)$ are given by the equations (see, for example [5], chapter 12):

$$\sigma\left(\Delta\tau\right)\approx(1/2\pi)\cdot(\Delta\nu)^{-1}\cdot(SNR)^{-1} \qquad (4)$$

$$\sigma(\Delta\theta) \approx (1/2\pi)\cdot(\lambda/b_{12})\cdot(SNR)^{-1} \quad (5)$$

where: $\Delta\nu$ - IF bandwidth, b_{12}-baseline of the space-based radio interferometer, λ - observing wavelength.

The anticipated signal-to-noise ratio (SNR) of an orbiting interferometer with a 4m diameter space radio telescope observing with a 70m ground-based telescope with system parameters of both space and ground telescope : Tsys= 50 K, T=300 see, Av =128 MHz will be SNR(1Jy)=1 00 and SNR(0.1Jy)=1 **O, respectively,** for an unresolved radio **source with** 1Jy **and** 0.1Jy flux density.

The estmated accuracy of the time delay $\sigma(\Delta\tau_{12})$ and angular mesurement $\sigma(\Delta\Theta)$ at λ -1 cm with such a system with a baseline between space radio telescope b_{12} - 50,000 km are given in Table 1:

SNR (1Jy) = 100	$\sigma(\Delta\tau_{12})$ -10-1 Isec	$\sigma(\Delta\Theta)$ -10 μarcsec
SNR (0.1Jy) = 10	$\sigma(\Delta\tau_{12})$ ~ 10^{-10} sec	$\sigma(\Delta\Theta)$ -102 μarcsec

2.4. Astrometry Improvements **Given Limitations of the Concept**

A variety of techniques to improve the accuracy of astrometry measurements with this system will be considered during this study:

1) If a bandwidth synthesis technique is used with the recorded bandwidth 128 MHz and VLBI channels spread on $\Delta\nu$ -3 GHz for sources with SNR(0.1Jy)=1O, the accuracy of angular measurements will be $\sigma(\Delta\Theta)$ - few μarcsec;

2) The proposed configuration of an orbiting radio interferometer enables, in principle, fringe phase measurements for astrometry instead of the usual group delay measurements as used in VLBI. The resulting accuracy of angular measurement with such system can be one to two orders of magnitude better than a VLBI interferometer measurement of tile time group delay [5];

3) Simultaneous observations in different frequency channels can be used to correct the dispersive interstellar and interplanetary plasma delays;

4) Using the phase referencing technique can improve SNR for weak radio sources measured relative to strong reference sources.

One of the important issues to be studied under this proposal is a need to take into account the source structure. Formally, equation (1) should have a term in it for radio source structure with will be different for two baselines, because they will be at two different hour angles. Each baseline is sensitive to a different spatial frequency of the source structure, producing a different group or phase delay. The effects are typically worse for group delay. The source structure effect can be an order of 100 rnicroarcseconds. To avoid this, different techniques will be considered including source structure modeling, using simultaneous multiwavelengths observations, repeating observations of the radio sources with different orientations of the baseline, Data on source structure from VSOP and Radioastron observations, if available, should be used for source structure effects modeling.

III. MISSION IMPLEMENTATION

3.1. Mission Design Requirements

This proposal is a feasibility study for an Astrometry VLBI in Space which should be implemented under the category of "Small Missions" (cost <$100 Mln). In order to meet this requirement, the mission design should be based on an existing (or feasible in near future) technology and existing supporting infrastructure. Following is an approach to developing a mission concept and the mission requirements.

3,2. **Spacecraft and** Science Payload

3.2.1. Science Payload

3.2.1.1. Space Radio Telescope Antenna.

The major cost driving element for SVLBI missions now under development or were considered as successors of VSOP and Radioastron is the cost of the space radio telescope antenna. The problem with

the large space antennas (more then 3-4m diameter) is that they must be deployable. Present launch vehicles can launch objects (antenna) with a maximum size of 3-4 m. Accordingly, it is difficult and expensive to satisfy the requirements of accuracy, dynamics, and reliability of deployment, The modest size, for ground based radio astronomy, 25m antenna (equivalent of VLBA antenna) will cost up to $1.50 to $200mln when if built for space [3]. This drives the cost of the mission itself to $500 mlrr and more,

In order to keep the cost of this mission low, the space-based antennas should be small, and non deployable. In such case, the size of the antenna will be limited to 3-4 m in diameter. Existing technology for space antennas [14] enables such an antenna to be built with an accuracy sufficient to operate up to 30-40 GHz. The mass of such an antenna is about 50 Kg.

3,2.1.2. Space Radio Telescope Receivers.

The key parameter of the space radio telescope, its sensitivity, is determined (along with the size of the antenna) by the noise temperature of its front-end. The development of new super-low-noise HEMT devices at X to Ka bands (8 to 32 GHz) is under development by the DSN Acivanced Technology program, During 1995-97, the HEMT LNA will be developed (including space qualified) with input noise temperature for cooled devices of: 2.4K at X-band, and 9K at Ka-band. This will permit a system temperature of 8 to 30 GHz even with a non cooled LNA well below 50K. The input bandwidth of such devices can be a few GHz.

3.2.1.3. Space Radio Telescope Observing Wavebands.

The choice of the space radio telescope's observing waveband is determined by the trade between the need to observe at the highest possible frequency to provide the highest angular resolution and the need to have a sufficient number of sources with unresolved by space interferorneter components to provide the signal-to-noise ratio SNR>10. The use of higher frequency bands will mean a decrease in the number of observable sources but also a decrease in interplanetary and interstellar scattering effects,

The wavebands considered as good candidates for this mission are 84, 22.2, 32, 43 GHz :

i) X-band (8.4 GHz) is the band where most ground-based VLBI astrometry rneasurements were made; the catalogs include -200 sources with S(8.4)> 0.1 Jy. The 8,4 G Hz band is used for communications with deep space spacecraft. The 32 GHz band is now under development by NASA for communication with future deep space missions. These two wavebands (X and Ka) can be used for radio astrometry experiments which involve tracking a spacecraft;

ii) 140 radio sources with S(22..2)>0,2 Jy were detected in ground-based 22. ? GHz VLBI prelaunch survey [15]. A number of H20 maser sources can be observed at this band;

iii) 43 GHz band is currently the highest frequency band in use by ground-based VLBI for routine observations;

iv) It was shown in [16] that 11 of 22 radio sources observed by the Earth-space radio interferometer with TDRSS (4.9 rn) on geostationary orbit and a 70m antenna on the ground were detected at 15 GHz and unresolved.

The above facts show that the proposed mission will have at least 100 possible sources for spacecraft-ground observations using a 70 meter antenna, down to 10-20 sources which could be observed directly with the two spacecraft,

3.2.1.4. Microwave Link between Space Radio Telescopes.

The proposed concept required to establish a two-way microwave (or laser) link between two orbiting spacecraft (space radio telescopes) in order to make distance measurements between the two spacecraft and synchronization of the space radio telescopes' local oscillators and clocks, The required accuracy for distance measurements between the two spacecraft is better than $c \cdot \sigma(\Delta\tau_{12}) \propto$ 1,0 cm,

A technique for the phase frequency transfer for orbiting VLBI radio telescopes which can satisfy the requirements of this mission has been developed [1 7], Establishing a microwave link with similar capabilities between spacecraft is being considered for the gravitational waves detection experiments ("Gravity Probe-A" [1 2], "SMILE" [1 8]). The study has shown that the technology exists to establish microwave links between spacecraft with required parameters at Ka and Ku bands (15 and 32 GHz). Through this techniques it should be possible to transfer the clock between the ground and the spacecraft to within a fractional frequency stability of 10-14 or better. By this means, a relatively inexpensive ultra-stable crystal oscillator will suffice as the on-board clock.

3.2.1.5. Optical Astrometry Subsystem,

The other major science payload system will bean optical package (optical astrometry subsystem) aligned with the radiometric antennas used for spacecraft-to-spacecraft ranging and time transfer. Each spacecraft opticalpackage should contain a very low power continuously operating laser and a small (- 10 cm diameter) telescope aimed at the other spacecraft. The optical system telescope can use CCD detectors capable of simultaneously observing the quasi-stationary laser beacon on the other spacecraft and stars passing through the field of view. The nominal magnitude limit for this system is 14th magnitude This subsystem should provide for measurements of a space radio telescope baseline orientation in an optical reference frame with an accuracy better than 0.001 arc sec.

3.2.2. Spacecraft

The spacecraft should provide three axes orientation with an accuracy when pointing along the axes of the space radio telescope antenna better than $\sigma(\Delta\Theta_{SRT}) \approx (1/10) \cdot \left(\lambda / D_{SRT}\right) \leq 40$ arc sec (here λ = 0.8 cm, D_{SRT}=4m). The stability of the pointing should be better than $\sigma(\Delta\Theta_{SRT}) / T \leq 0.1$ arcsec/sec (here T=300 sec - integration time).

The spacecraft should provide a permanent simultaneous microwave link with other spacecraft (space radio telescope) and a microwave link with ground-based tracking stations for synchronization of the local oscillators and clocks. A 50crn diameter antenna with a few Watts transmitter power should be enough to establish these links at Ku-band (15 GHz). The microwave link with ground stations should be established also for data transrnission from the spacecraft to the ground at the rate of up to 256 Mbit/sec.

3.3. **Ground Support**

3.3.1. Ground Telescopes For SVLBI Co-Observing

The effectiveness (scientific return) of the proposed mission crucially depends on the support of large ground-based radio telescopes.

The 70m DSN antennas routinely provide VLBI observations at 8.4 and 22 GHz. The efficiency of these antennas at 22 GHz is about 50%. The DSN Advanced Technology Program foresees the development of 32 GHz receiving capability at the 70m DSN antennas. The anticipated efficiency of these antennas at 32 GHz is about 30%. The new generation of low noise HEMT LNAs with anticipated input noise temperature of 2.4K and 9K at 8 and 32 GHz respectively, is now under development at the DSN. The array of a new 34m high efficiency beam waveguide antennas is under construction by the DSN. The efficiency of the existing prototype of this antenna in Goldstone at 43 GHz is 50°/0. The DSN plans to upgrade the existing MKIIIA recording capabilities at the DSN sites to MKIV before 1997 in order to provide co-observing support for the SVLBI missions, VSOP and Radioastron.

The 43 GHz VLBI observations are now routinely provided by the major VLBI radio astronomy networks, the EVN and the VLBA. The Effelsberg 100m radio telescope, the VLA phase array and newly developed Green Bank 100m.

3.3.2. O VLBI Tracking Network at the DSN

The data from the space radio telescope should be transmitted directly to the Earth without storage onboard; the s/c should not carry a high stable frequency standard - the necessary L.O. synchronization should be executed through microwave links from the Earth. The Orbiting VLBI subnetwork built by the DSN for tracking support of the current SVLBI missions, VSOP and Radioastron, can be used to support the proposed mission [9]. Currently, the design parameters of the OVLBI subnet are:

- X and Ku bands (8.4 and 15 GHz) are used for communication with spacecraft;
- the bandwidth of the signal transmitted to the Earth is 64 to 128 MHz;
- the two-way coherence link between the ground Tracking Station (TS) and spacecraft will allow a signal decorrelation loss for observations with an Earth-space radio interferometer of no more than 1 % at 22 GHz for 300 sec of integration time; this performance corresponds to an rrns phase error -11 deg at 22 GHz;
- -11 m diameter OVLBI antenna is sufficient for synchronization and data transmission for distances up to 100,000 km.

3.3.3. USNO VLBI Correlator

The US Naval Observatory correlator is a MKIII correlator which mainly processes data of the geodetic VLBI network. Additionally, it allocates a relatively small time for data processing of other research projects. The prototype of this correlator was used for data processing of the first SVLBI experiment with the communication satellite TDRSS in 1986. Currently, the correlator has 6 playbacks (two MKIV and 4 MKIIIA) and can be used for data processing of 6 stations simultaneously. The correlator has software to process not only continuum sources but also pulsars and maser sources.

There is a plan to upgrade the correlator to MKIV during the next couple of years which will enable the correlator to process the data from the proposed Astrometry VLBI in Space. It also will enable the correlator to process data from the VLBI astrometry experiments in order 10 prepare for proposed mission and from the SVLBI missions, Radioastron and VSOP.

3.4. **Launch and Orbit**

Preliminary consideration show that the mission can be launched on a Russian Proton booster. The booster can launch up to 2.2 metric tons to the geostationary orbit. It is possible to launch two-three spacecraft simultaneously. There are three payload fairings available for use with the Proton. The usable volumes of Models A and B are both 3.3 m in diameter and 4.2 and 6.1 m long, respectively. Model C has a usable volume that is 4.1 m in diameter and 7.5 m long.

Another option is to launch two spacecraft by two separate Russian Molniya launchers with the "Fregat" kick motors to deliver the spacecraft into the geostationary orbit. 1 he mass capability of the two boosters is approximately the same.

In order to simplify both spacecraft design and lower ground station costs, the satellites can be placed in near equatorial geosynchronous orbits, with the satellite separation being the same as the semi-major axis (36,000 km), which should help to remove systematic effects due to source structure.

If SRTS will be launched in a geostationary orbit, the baseline for a space-based radio interferometer can be as long as 50,000-70,000 km.

3.5. **Orbit and System Geometry Determination**

Meeting the mission astrometric accuracy goals will require knowledge of the baseline vectors at the < 1 cm level.

The continual spacecraft-spacecraft and spacecraft-ground radiometric tracking will determine (using one ground station) the exact size and shape of the triangle between the Earth geocenter and the two spacecraft, but will not provide the orientation of that triangle with respect to an inertial frame. In order to meet the primary mission goals, the spacecraft orbital stability must be sufficient to estimate the baseline orientation directly from the VLBI data by combining data from different scans at different times. In order to facilitate this, and to provide an independent check of the results, the spacecraft-spacecraft vector will be determined independently during each scan (observation of a specific source at a specific time),

A variety of techniques for doing this will be explored during the mission feasibility and design study, including VLBI tracking of radio beacons on each spacecraft and tracking by each spacecraft of Global Positioning System satellites, But it is expected that the primary technique for determining the baseline orientation will be double differencing of time transfer/ tracking signals received at the primary and secondary ground stations, coupled with simultaneous VLBI observations of the target source or other astrometric sources at the secondary stations.

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